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Concrete mixes: specification, design and quality control

The digest describes the different ways in which concrete can be specified, with particular reference to BS 5328 and to CP 110. It discusses the variability of concrete in production, the requirements for quality control and the statistical aspects of testing for compliance with a specification. It describes the main factors influencing the strength and workability of concrete in relation to the mix design method described in Design of normal concrete mixes. *Materials for concrete are described in Digest 237.*

This digest replaces Digest 13 which is now withdrawn.

Developments in specifications in the 1970s.

Differences in properties occur in all constructional materials. In building and civil engineering much attention is given to the variability of the compressive strength of concrete. Manufactured materials, such as steel and bricks, and natural materials, such as timber or stone, have accepted properties and can be tested before use in a structure. Unless exposed to a harmful environment their strength remains sensibly constant with time. However, concrete can be produced on site or delivered ready-mixed and its properties, particularly its compressive strength, change with time and cannot be established until after the concrete is in the structure.

Knowledge of the concrete strength is required both for assurance of its structural adequacy and for contractural assurance that it complies with the client's specification. It is probably due to this second requirement that so much attention has been paid to the variability of the strength of concrete.

Concrete can be produced having a wide range of properties, including strength, depending on the materials and mix proportions used. The quality of concrete to meet requirements for strength, durability and other properties can be specified either in terms of mix proportions or performance. For many years mix proportions have been specified as 'nominal' volumetric proportions such as 1:2:4 of cement/fine aggregate/coarse aggregate but the modern method is to specify the cement content in kilograms per cubic metre of fresh concrete. The performance requirement most usually specified is compressive strength at 28 days.

During the 1970s there were considerable developments both in the UK and abroad in standardising the descriptions of concrete mixes, in limiting the variety of concrete grades to be specified and in the methods of testing concrete. A common approach to compliance with specifications based on statistical principles has also been developed.

The international organisations involved in this work include the Euro-International Committee for Concrete (CEB) and the International Standards Organisation (ISO) The CEB/FIP Model Code for Concrete Structures[1] was published in 1978. Such work has influenced the content of British Standards such as BS 5328 *Methods for specifying concrete* and CP 110 *The structural use of concrete.*

BS 5328 was produced in 1976 but the work of its drafting committee influenced the content of Section 6 of CP 110 published in 1972. Although following the same principles there are differences between these two documents due partly to their differences in scope. BS 5328 covers methods for specifying concrete suitable for all applications and the means of checking compliance with the specification. CP 110 deals with the structural use of concrete in buildings and structures; since it covers a more restricted field of concrete use it give more advice to the engineer on the selection of the materials and mixes to be used in particular situations and gives more requirements relating to workmanship in the production and placing of concrete.

Neither of these documents includes specific details of concrete mix design although CP 110 gives requirements for fixing the target mean strength higher than the specified strength used in the structural design. *Design of normal concrete mixes*[2] was published in 1975 and provides a method, described later, for designing concrete mixes suitable for most applications.

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Variability of concrete strength

Factors influencing compressive strength

Many factors influence the compressive strength of concrete and must be allowed for both in the specification and the design of the concrete mix. The most significant ones are discussed in *Design of normal concrete mixes* and are as follows:

Age at test and curing conditions Under favourable conditions of curing, both of temperature and humidity, the strength of concrete increases with age. Most specifications require concrete test specimens to be cured under the standard conditions specified in BS 1881: Part 3 and tested at 28 days after being cast.

Type and strength of cement Different types of cement produce concretes having different rates of strength development (Digest 237). The strength of the concrete will also be affected by the variability of a particular type of cement obtained from different works and by the normal variations in production for any one works.

Type and grading of aggregates Crushed rock aggregates tend to make stronger concrete for the same cement content as concrete made with uncrushed aggregates but require higher water contents to maintain the same workability. The grading, particularly of fine aggregate, also affects the water demand and hence the strength of the concrete. Research using crushed rock aggregates from 24 different sources[3] showed that the water demand varied from 170-230 kg/m³ (Digest 237) resulting in different free water/cement ratios and consequently a range of compressive strengths at 28 days of more than 20/mm², as shown in Fig. 1.

Free water/cement ratio This is the major factor in concrete mix design affecting the strength of concrete (see Figure 3). Together with the water content required for workability it determines the cement content of the mix.

Overall variation on site and its measurement

On any given site the materials used may come from a few sources, although in many cases there may be a single source for cement and a single source for aggregates. Even so, their properties will vary over the period of construction. This variability contributes to the overall variation in the measured strength of concrete, which arises from the component materials, the production process (ie plant control, resulting in changes from the intended mix proportions) and the sampling, making and testing of concrete specimens. It is difficult to determine the proportion of the overall variation arising from each of these sources[4].

The variation in concrete strength typically obtained from tests at a site is shown in Figure 2; there are more results close to the mean value and less at the extremes. It is now accepted that the variation in concrete strengths follows a normal distribution curve illustrated to the right in Figure 2. The area beneath the curve represents the total number of results, and the proportion of results less than some specified value is represented by the area beneath the line at the specified value and the curve. In Figure 2, five per cent of the results are shown as being less than 30 N/mm². The normal distribution curve is symmetrical about its mean and is completely specified by two parameters, its mean m and its standard deviation s, the latter being a measure of variability, calculated from the equation:

$$s = \sqrt{\frac{\Sigma (x - m)^2}{n - 1}}$$

where x = an individual result
n = the number of results
m = the mean of the n results

With poor quality control there is a wide scatter of results giving a high standard deviation; the better the control the lower the standard deviation and the sharper the normal distribution curve.

Due to the distribution of results there is always the probability, however, remote, that a result less than the specified strength will be obtained. It has now become general practice to specify not a minimum strength but a 'characteristic strength' below which a specified proportion of the test results, often called 'defectives', may be expected to fall. The characteristic strength may be defined to have any proportion of defectives; BS 5328, CP 110 and the International CEB/FIP Model Code have all adopted a five per cent level of defectives for concrete. Thus, the characteristic strength of concrete is defined as "that value of strength below which five per cent of the population of all possible strength measurements of the specified concrete are expected to fall".

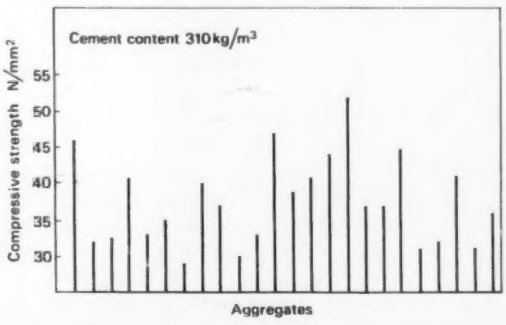

Fig 1 Effect of using 24 different aggregates on the compressive strength of concrete at 28 days

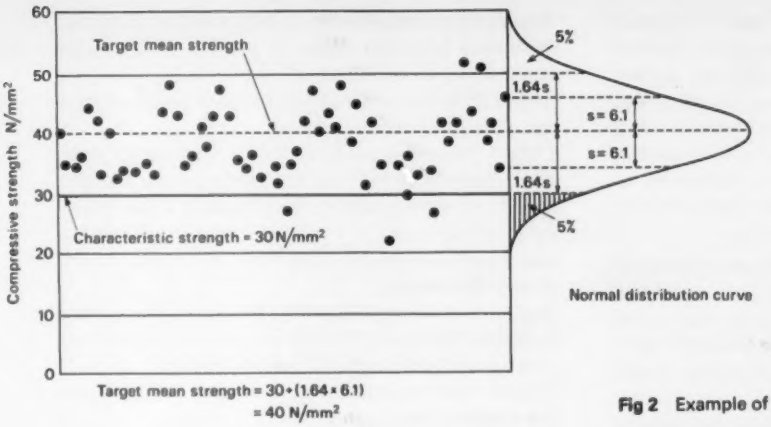

Fig 2 Example of variation in concrete strength on one site

Margins required for mix design

Because of the variability of concrete strength, the mix must be designed to have a mean strength greater than the specified characteristic strength by an amount termed the 'margin'. Thus

$$f_m = f_c + ks$$

where f_m = the target mean strength

f_c = the specified characteristic strength

ks = the margin, ie the product of

s = the standard deviation

k = a statistical constant.

The statistical constant k is derived from the mathematics of the normal distribution and increases as the proportion of defectives is decreased; for example:

k = 1.28 for 10 per cent defectives

k = 1.64 for 5 per cent defectives

k = 2.33 for 1 per cent defectives.

For concrete having a five per cent defective level, k = 1.64 and the margin is 1.64 s. Figure 2 shows a concrete having a specified characteristic strength of 30 N/mm² and a standard deviation of 6.1 N/mm².

Hence the margin = 1.64 x 6.1 = 10N/mm² and the target mean strength = 30 + 10 = 40N/mm²

The margin used in mix design depends upon the magnitude of the standard deviation to be expected for a given job. In many cases there is previous information on the standard deviation to be expected (with ready-mixed concrete, for example). The reliability of the value of the standard deviation increases with the number of results used in its calculation and it is generally recommended that at least 40 results are used.

The magnitude of the standard deviation varies from site to site: in the United Kingdom it is seldom less than 2.5 N/mm² or more than 8.5 N/mm². A survey of the variability of concrete strengths from construction sites has been made by the Transport and Road Research Laboratory[5] and some data from the survey are given in Table 1. They show that the mean standard deviation is about 5.5 N/mm² and that 80 per cent of sites have a standard deviation between about 3.5 N/mm² and 7.5 N/mm².

There has been considerable discussion[4] as to whether the standard deviation obtained at a single site is dependent on the mean strength of concrete being produced. It is now accepted that the standard deviation increases with the mean strength of the concrete up to a strength of 20 N/mm², but that above this value the standard deviation remains sensibly constant. This approach is followed in CP 110 in the requirements for deciding on the margin for designed mixes.

Table 1 Distribution of standard deviation (from TRRL Report LR 300)

Source	Standard deviation *N/mm²*		
	10 per cent of sites less than	Mean	10 per cent of sites more than
Figure 8 of LR300			
TRRL survey	3.4	4.9	7.3
Ealier C & CA survey	4.1	5.5	7.3
Figure 10 of LR 300			
Site mixed concrete	4.0	5.2	6.9
Ready mixed concrete	4.8	5.6	7.6

Concrete mix design

Objectives

In the broadest sense the purpose of mix design is to select the most appropriate materials and their relative porportions so that the concrete produced has the specified properties. Generally concrete mixes are designed to meet the specified requirements for strength and workability, although in some cases other requirements have to be met. Concretes having lower densities are required for better thermal insulation (Digest 123) and this may involve the use of lightweight aggregates[6], such concretes also have improved fire resistance. The production of concrete having other specific properties, such as low drying shrinkage (Digest 35) or particular ranges of elastic modulus[7] involve careful selection of the source of the aggregate. Concrete also has to be durable, sometimes under severe environmental conditions[8], for example being subjected to frost action or sulphate attack (Digest 174).

These situations may require the use of special cements or admixtures (Digest 237), and place limiting values on mix proportions such as minimum cement contents and maximum free-water/cement ratios. For structural concrete CP 110 includes such requirements for durability and these must always override the mix proportions obtained from designing mixes solely to meet strength and workability requirements.

Design of normal concrete mixes: Scope

This method is restricted to designing concrete mixes to meet specified workability and compressive strength requirements using ordinary or rapid-hardening Portland cements complying with BS 12 or sulphate-resisting Portland cement complying with BS 4027, and natural aggregates to BS 882 or coarse air-cooled slag to BS 1047. It does not deal with special cements or special concretes such as lightweight aggregate concrete, but it does include air-entrained concrete and mixes designed for indirect-tensile strength often required for use in concrete pavements[9]
The mix design process takes account of those factors that have a major effect on the strength and workability of concrete as outlined earlier. There is little point in the mix design allowing for secondary factors which are difficult to measure or which are unlikely to remain constant during the progress of the job. It is possible that the target values might not be achieved, owing to the component materials varying from source to source; in such cases the mix proportions can be adjusted from the results of trial mixes.

Part One of *Design of normal concrete mixes* gives the basic information which is required to understand the mix design procedure. Part Two describes the method and contains tables and graphs of the data needed for its application. As a simplification only two types of aggregate are considered, crushed and uncrushed. Crushed aggregates require a higher water content than uncrushed aggregates to make concrete having the same workability. However, this extra water does not result in a lower strength since concrete made with crushed aggregates is generally stronger than concrete having the same free-water/cement ratio made with uncrushed aggregates.

Design of normal concrete mixes: Method

To design the mix the producere requires the following minimum information as specified variables:-

(a) the characteristic strength
(b) the type of cement
(c) the workability (slump or VB)
(d) the maximum size of aggregate.

In addition, the producer requires the following information which is usually available from his previous experience:-

(a) the standard deviation (or assumed value)
(b) the type of aggregate (crushed or uncrushed)
(c) the relative density of the aggregate (or assumed value)
(d) the grading zone of the fine aggregate. (See BS 882)

The method consists of five separate stages each dealing with a particular aspect of the mix design. Each stage yields an important mix parameter or final mix proportions expressed as kilograms of a material per cubic metre of fresh concretee.

Stage 1 concerns strength. The target mean strength is calculated from the specified characteristic strength and the standard deviation (see Figure 2). From knowledge of the types of materials to be used and the relationship shown in Figure 3 the free-water/cement ratio is determined.

Stage 2 concerns workability. The free-water content is determined from the specified workability and the type and maximum size of the aggregate.

Stage 3 combines the results of Stages 1 and 2 to give the cement content.

Stage 4 is the determination of the total aggregate content using the known or assumed relative density of the aggregates.

Stage 5 is the selection, based on the grading zones of BS 882, of the fine and coarse aggregate contents.

The method provides for the use of overriding values of maximum free-water/cement ratio, or maximum or minimum cement contents if these are specified for any purpose, such as durability requirements.

Figure 3 shows a group of typical relationships between the compressive strength of concrete and the free-water/cement ratio. For convenience they are spaced at 5 N/mm² or 10 N/mm² intervals at a free-water/cement ratio of 0.5 which is used as the starting point for the design of concrete mixes. With ordinary Portland cement and uncrushed aggregates the strength at 28 days is 40 N/mm² (Point A); with crushed aggregates the strength is 47 N/mm² (Point B).

Specification of concrete mixes

Types of mix

To obtain concrete of the required performance the purchaser must inform the producer of his requirements; this is done by a specification defining the types of materials, cement, aggregate and admixtures that may or may not be used and the proportions in which they are mixed.

The selection of mix proportions may be made by the purchaser, or by the producer to meet the required performance as specified by the purchaser.

In earlier codes of practice, such as CP 114, nominal mix proportions were linked to a 28-day strength requirement. To allow for the variability during production such codes required a higher strength from the preliminary trial mixes than from the production works tests. Thus a nominal 1:2:4 mix required a preliminary strength of 28 N/mm² at 28 days for a works strength of 21 N/mm².

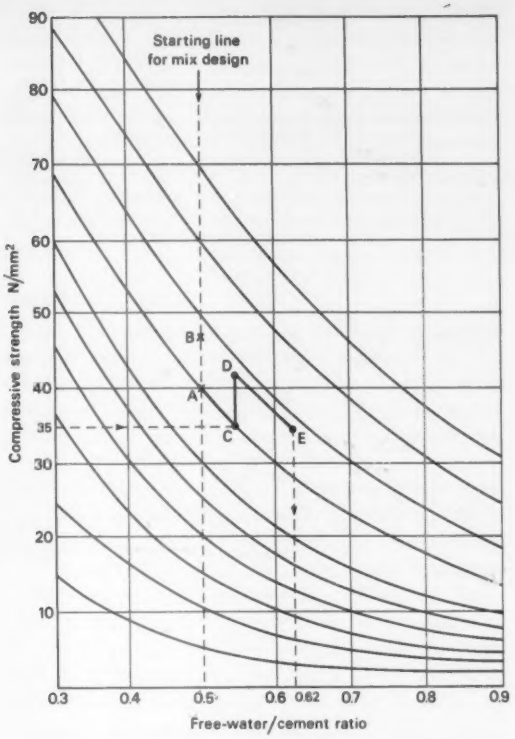

Fig 3 Relationships between compressive strength of concrete and free-water/cement ratio.
Example Starting point, 28-day strength with ordinary Portland cement and uncrushed aggregates, 40 N/mm²: Point A
Required target mean strength 35 N/mm², *free-w/c ratio 0.54: Point C*
Trial mix results 42N/mm²: Point D
Adjusted free-w/c ratio 0.62: Point E

In modern codes of practice, such as CP 110 and BS 5400, a clear distinction is made between the specification of mixes by performance, these being called *designed mixes,* and those by mix proportions termed *prescribed mixes.* In the latter case a distinction is also made between those mix proportions given in a national code or standard and special mix proportions chosen and specified by the purchaser. These different types of mix are used in BS 5328 but a simpler terminology is used in the CEB/FIP Model Code:

BS 5328	CEB/FIP Model Code
Designed mix	Designed mix
Ordinary prescribed mix	Standard mix
Special prescribed mix	Prescribed mix

These three types of concrete mix require different types of specification owing to differences in the responsibility for the mix design, the grades of concrete and the materials that can be used, and in the criteria used for judging compliance. These differences are shown in Table 2.

Table 2 Characteristics of different types of concrete mix

	Designed mix	Standard mix	Prescribed mix
Responsibility for mix design	Producer	Purchaser selects from BS 5328 or CP 110	Purchaser
Permitted grades	All grades	C7.5-C30	All grades
Permitted materials	Generally complying with a wide range of British Standards	Cements to BS 12, BS 146 and BS 4027. Aggregates to BS 882, BS 1047 No admixtures	Purchaser free to specify or to restrict any material
Main criterion used for judgment of compliance	Strength	Mix proportions	Mix proportions

Grades of concrete and their use

Among the objectives in producing BS 5328 was to reduce the number of grades of concrete specified by authorities and purchasers, and to produce a standardised format for specifying concrete. For all three types of mix BS 5328 requires the specification of the quality of concrete in terms of a 28-day characteristic strength grade. In the majority of cases this is a compressive strength grade but BS 5328 includes flexural and indirect-tensile strength grades. With designed mixes a minimum cement content is also specified whereas for standard or prescribed mixes the actual cement content or mix proportions are specified. BS 5328 includes standard forms for specifying the requirements for the different types of mix. For structural concrete, CP 110 places limitations on the grade of concrete according to its use. The grades of concrete to be specified, which comply with the International Standard ISO 3893[10], and their application with minimum cement contents for different uses of concrete are given in Table 3.

Designed mixes

With designed mixes the purchaser is responsible for specifying the required performance of the concrete in terms of one of the grades given in Table 3 and the producer is responsible for designing the mix to give the required performance. The cement contents given in Table 3 should be regarded as 'long-stops': in many cases higher cement contents will be required to produce the required grade of concrete. Furthermore, the purchaser should consider requirements for durability which may need the specification of special cements or limitations on mix parameters such as higher minimum cement contents or lower maximum free-water/cement ratios. Digest 174 deals with concrete in sulphate-bearing soils and guidance on the specification of concrete mixes to meet durability requirements is given in codes of practice, such as CP 110.

Standard mixes

Standard mixes are provided in BS 5328 and CP 110 for use on small jobs which do not justify the application of mix design, or to enable work to start when there is a lack of previous data on the materials and production control. Standard mixes are those designed on a national basis to provide concrete of the appropriate grade. The mixes given in BS 5328 and CP 110 have cement contents more appropriate to the required strength than do the nominal mixes in CP 114, which they replace. They allow for two levels of workability, different maximum sizes of aggregate and different fine aggregate gradings. As seen from Table 2 they are restricted to the lower grades of concrete, and to the more common types of cement and aggregate. Admixtures may not be used with standard mixes.

Owing to the variability of materials from different sources a high margin has been used and so the cement contents are likely to be higher than for a corresponding designed mix. Standard mixes may be expressed in terms of cement and aggregate contents per cubic metre of fresh concrete, or in terms of quantity of aggregates per 100 kg (2 bags) of cement. The former method is preferable and standards and codes usually allow for slight adjustments to the standard mixes to take account of the materials actually used.

It is the purchaser's responsibility to select a standard mix to meet his strength and durability requirements; the producer is then responsible for supplying the specified mix. It should be noted that strength testing for compliance is not appropriate for standard mixes although if required the purchaser could make strength tests to assure himself that the standard mix he specified is appropriate.

Table 3 Grades of concretes

Grade	Characterisitic compressive strength at 28 days N/mm^2	Lowest grade permitted for use in	Minimum cement content for use in	
			Plain concrete kg/m^3	Reinforced or prestressed concrete kg/m^3
C 7.5	7.5	concrete not containing embedded metal	120	-
C 10	10.0		150	-
C 15	15.0	Reinforced concrete with lightweight aggregate	180	240
C 20	20.0	Reinforced concrete with dense aggregate	220	240
C 25	25.0			
C 30	30.0	Concrete with post-tensioned tendons		300
C 35	35.0			
C 40	40.0	Concrete with pre-tensioned tendons		300
C 45	45.0			
C 50	50.0			
C 55	55.0			
C 60	60.0			

Prescribed mixes

With prescribed mixes the purchaser takes full responsibility for the design of the mix to produce concrete having the required properties. The purchaser can specify precisely the materials, including admixtures, and the mix proportions to be used. For example, he may specify a particular source of aggregate so that the colour of the concrete matches some existing concrete, or a particular lightweight aggregate so that a specified low density concrete is produced.

With prescribed mixes, as with standard mixes, the main compliance requirement is based on the assessment of the mix proportions used. Any special tests should be agreed between the purchaser and the producer before the job starts.

Concrete production, quality control and compliance

Production

It is often said that when a purchaser specifies concrete by a performance requirement, such as compressive strength with designed mixes, the means by which the concrete is produced should be left to the producer. However, not every batch is tested and there are properties of concrete other than strength essential for good performance which require the use of good production methods.

BS 5328 gives requirements for:

(a) methods of batching materials
(b) accuracy and maintenance of measuring equipment
(c) performance of concrete mixers.

In addition, codes of practice, such as CP 110, give more practical details such as:

(a) requirements for supervisory personnel
(b) storage and handling of materials
(c) working in hot and cold weather conditions
(d) production control techniques
(e) transporting, placing and compacting concrete
(f) curing concrete.

Quality control

The aim of quality control is to produce concrete to the required specification with a minimum of variation from batch to batch. The overall control of quality consists of two distinct, but interconnected parts: production contol and compliance testing.

Production control is used to produce an economical material having only a small chance of not complying with the specification. It involves checking and testing the materials and the concrete produced to obtain a feedback and adjustment to the production process. This may include accelerated strength testing and the use of sophisticated statistical techniques.

Compliance testing is carried out by the purchaser to ensure that the concrete produced complies with the specification. Testing and production control, therefore, provide the overall assurance of quality. Under different situations the relative significance of these two aspects may vary. In one case the producer may have simple control with great reliance placed on compliance testing, whereas in another case, the purchaser could rely entirely on the producer's control and test procedures.

Compliance testing

If certain materials have been specified, eg special types of cement or aggregates, compliance can be checked by inspection of the materials, delivery tickets and manufacturer's test certificates. Samples of the materials may be taken and tested to check compliance with the specification or British Standard.

If the workability, air content or density of the fresh concrete is specified, the concrete can be checked for compliance by testing in accordance with the relevant requirements of BS 1881. The same limits for acceptance are given in BS 5328 and CP 110.

The greatest problem in testing for compliance is to ensure that the mix supplied is of the quality specified. For standard and prescribed mixes compliance is in terms of the composition of the mix and BS 5328 provides two procedures. First, by observation of the batching process or by examining autographic records, and second, by using methods of analysis of fresh concrete; these methods require considerable time and technical skill to avoid substantial testing errors.

Strength compliance of designed mixes

With designed mixes the main criterion for juding the quality of the concrete is the compressive strength at 28 days. The use of the characteristic strength concept complicates the problem of testing for compliance. By definition, test results lower than the specified strength will occur and are acceptable provided that the specified level of defectives (five per cent) is not exceeded. It is not necessary to test 100 specimens; various testing schemes can be developed from statistical principles using only small groups of test results.

With any compliance testing scheme there is always the chance that concrete of the required quality is indicated as not complying with the testing scheme (producer's risk), or that concrete of an inferior quality is indicated as complying (consumer's or purchaser's risk). These risks depend largely on the testing scheme adopted. The producer can reduce his risk by producing concrete having a lower level of defectives than the specified five per cent. This is achieved by increasing the mean strength of the concrete. The increased material cost should be balanced against savings from fewer non-compliance disputes.

The effect of using different compliance shcemes on the producer's and purchaser's risk is compared by means of Operating Characteristic curves (O-C curves). An O-C curve is a graphical presentation showing the probability that a quantity of concrete containing a given level of defectives will be accepted by the compliance scheme. Such curves are described in BS 2846: Part 5, and those resulting from the requirements of different specifications and codes of practice are described in References (11) and (12).

The compliance scheme given in BS 5328 is based on the running mean of groups of four results, ie

results: 1, 2, 3, 4	group 1
results: 2, 3, 4, 5	group 2
results: 3, 4, 5, 6	group 3
results: 4, 5, 6, 7	group 4

For concrete of grade C 20 and above the compliance requirements of BS 5328 are that:

(a) the average strength determined from any group of four consecutive test results exceeds the specified characteristic strength by 3 N/mm², and

(b) the strength determined from any test result is not less than the specified characteristic strength minus 3 N/mm².

Thus, if concrete grade C 25 is specified, the concrete complies with the specification provided that the average of any four consecutive results is not less than 28 N/mm² and no individual result is less than 22 N/mm².

Figure 4 shows three O-C curves. Curve A is the ideal (but unattainable) for concrete based on a five per cent defective characteristic strength. Curve B is for a single test based on a specification that no single test result shall fall below the specified strength. Curve C is for the running mean of four results, as given in BS 5328, when the standard deviation is 5 N/mm² (about average for concrete produced in the UK). Concrete with five per cent defectives will produce a 94 per cent probability of acceptance under this scheme. For higher or lower standard deviations, the O-C curve moves up or down respectively. If, as in some codes, the compliance function includes the standard deviation, a

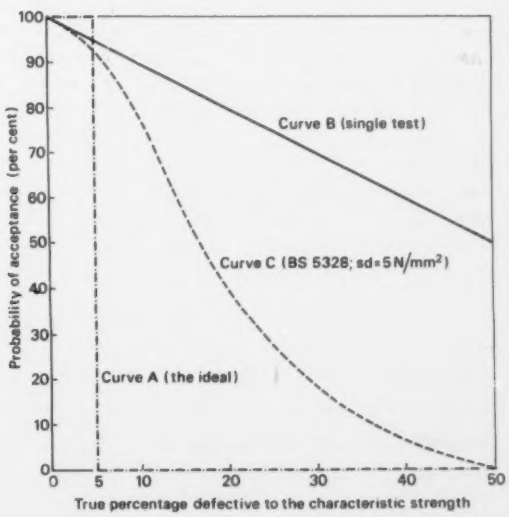

Fig 4 Operating characteristic curves for various testing plans

fixed O-C curve is obtained. However, there is then an uncertainty due to the unreliability of estimating the standard deviation and of using past data applied to current production.

Although O-C curves are useful for comparing various compliance schemes they should not be used alone to comapre the economic risks of different schemes. The economics depend on the complete control system and are influenced by the rate of sampling, the number of specimens made, the compliance function, the quantity of concrete under judgement and the action taken in the event of non-compliance with the testing plan.

Test results indicating non-compliance should not mean automatic rejection of the concrete since, as has been mentioned, there is a chance that a concrete indicated as non-complying does in fact comply. Such results merit further consideration. The action taken may range from qualified acceptance in less severe cases to rejection and removal of the concrete in the more severe. It may also be necessary to modify the concrete mix to ensure that in future the concrete produced complies with the specification.

References

1 CEB-FIB Model code for concrete structures. 3rd edition, 1978.
Comite Euro-International du béton. Paris.
2 Design of normal concrete mixes. HMSO, 1975.
3 Teychenne, D.C. The use of crushed rock aggregate in concrete; BRE, 1978.
4 Teychenne, D.C. Recommendations for the treatment of the variations of concrete strength in codes of practice. BRE Current Paper CP6/74.
5 Metcalf, J.B. The specification of concrete strength: Part 2. The distribution of strength of concrete for structures in current practice. RRL Report LR 300, 1970.
6 Short A and Kinniburgh W. Lightweight concrete. 3rd edition, 1978, Applied Science Publishers Ltd, London.
7 Teychenne, D C, Parrot, L J and Pemfroy, C D. The estimation of the elastic modulus of concrete for the design of structures. BRE Current Paper CP23/78.
8 Gutt, W and Harrison, W H. Chemical resistance of concrete. BRE Current Paper CP23/77.
9 Specification for road and bridge works. HMSO, 1976.
10 Concrete - Classification by compressive strengths. International Standard ISO 3893: 1977.
11 Metcalf, J B. The specification of concrete strength: Part 1. The statistical implications of some current specifications and codes of practice. RRL Report LR 299, 1970.
12 Mathews, D H and Metcalf, J B. The specification of concrete strength: Part 3. The design of acceptance criteria for the strength of concretes. RRL Report LR 301, 1970.

Documents referred to in the text.

BRE Digests

35 Shrinkage of natural aggregates in concrete.
111 Lightweight aggregate concretes: Structural applications.
123 Lightweight aggregate concretes.
174 Concrete in sulphate-bearing soils and groundwaters.
237 Materials for concrete.

British Standards

BS 12: 1978 Ordinary and rapid-hardening Portland cement.
BS 882, 1201: 1973 Aggregates from natural sources for concrete (including granolithic).
BS 1047: 1974 Air-cooled blastfurnace slag coarse aggregate for concrete.
BS 1881: Parts 1-5: 1970 Methods of testing concrete.
BS 2846: Part 5:1977 Power of tests relating to means and variances.
BS 4027: 1980 Sulphate-resisting Portland cement.
BS 5328: 1976 Methods for specifying concrete.
BS 5400 Steel, concrete and composite bridges.
Part 7:1978 Specification for materials and workmanship: concrete, reinforcement and prestressing tendons.
Part 8:1978 Recommendations for materials and workmanship: concrete, reinforcement and prestressing tendons.
BS CP 110 The structural use of concrete.
Part 1: 1972 Design, materials and workmanship.
BS CP 114:1969 Structural use of reinforced concrete in buildings.

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